

All optical diode based on dipole modes of Kerr microcavity in asymmetric L-shaped photonic crystal waveguide

E. N. Bulgakov and A. F. Sadreev*

*Kirensky Institute of Physics, Siberian Branch of Russian Academy of Sciences,
660036, Krasnoyarsk, Russia *Corresponding author: almas@tnp.krasn.ru*

A design of all optical diode in L -shaped photonic crystal waveguide is proposed that uses the multistability of single nonlinear Kerr microcavity with two dipole modes. Asymmetry of the waveguide is achieved by difference in coupling of the dipole modes with the left and right legs of waveguide. By use of coupled mode theory we present domains in axis of light frequency and amplitude where an extremely high transmission contrast can be achieved. The direction of optical diode transmission can be governed by power and frequency of injecting light. The theory agrees with numerical solution of the Maxwell equations.

PACS numbers: (130.5296), (190.3270), (190.4360), (230.4320).

The optical bistability performance of a spatially asymmetric photonic crystal (PhC) structure together puts the structure to be a device that is called all-optical diode (AOD). Such a device transmits light from one side of the structure but not from other side. The optical diode has an analogue with semiconductor diode that passes electricity from one side only. AOD device plays important role in all optical signal processing. The first proposal for PhC-based optical diodes was suggested by Scalora *et al* [1] based on the dynamical shift of the photonic band edges in the 1D structure that consists of alternate stacks of linear and nonlinear layers. After several years, Gallo and Assanto [2] demonstrated that AOD can be created by exploiting a $LiNiO_3$ waveguide with gratings. Optical diode is characterized by the transmission contrast $\eta = T_L/T_R$ where T_L and T_R are the left and right transmissions, respectively.

Up to now, many different mechanisms and methods to achieve optical diodes have been proposed (see Ref. [3] and references there). Among of them nonlinear cavities with different confinement strengths along the left and right sides were used to give rise to unidirectional transmission [4–6]. Because of the asymmetric confinement, the threshold for the transmission through in-channel nonlinear cavities depends on the launch direction of the input wave. However in spite of the merits of AOD structures, the transmission contrast η is usually low. In experiments by Gallo and Assanto the transmission contrast was only $\eta = 0.9$, although the CMT and FDTD simulations for single nonlinear cavity showed $\eta = 7.2$ [6]. Ultra high-contrast was demonstrated in silicon Fano diode [3] $\eta = 500$ with use of two uncoupled nonlinear micro cavities in PhC directional waveguide with $T_L = 0.7$ and $T_R = 0.0014$. In present paper we consider the AOD design exploring the asymmetric PhC L -shaped waveguide with single nonlinear microcavity at corner whose two degenerated dipole eigen modes lie in the propagation band of the PhC waveguide. An asymmetry of the design is achieved owe to different coupling strengths of dipole modes with propagating mode of the waveguide in the left and right legs. Such AOD design demonstrates ultra high transmission contrast with $T_L = 0.9$ and $T_R = 0$ in the framework of CMT as well as $T_L = 0.95$ and $T_R = 10^{-5}$ in the framework of numerical computation of the Maxwell equations in PhC structure.

Unique symmetry properties of dipole modes of linear cavity has been first demonstrated in cross waveguide in seminal paper by Johnson *et al* [7]. Yanik *et al* [8] considered the nonlinear cavity of elliptic shape defect rod with two dipole modes at the center of the cross photonic crystal (PhC) waveguide. They have shown that due to a nonlinearity of the cavity transmission over the x -direction can be reversibly switched on/off by a control power over the y -direction to realize all-optical transistor in X-shaped waveguide. Recently we have shown that the nonlinear cavity with two degenerated dipole modes positioned at the center of the directional waveguide can operate in two regimes under transmission of even propagating mode [9]. The first regime inherits the linear case when transmitting light excites only the even dipole mode blocking outputs into perpendicular directions. However with increasing of injecting power a bifurcation with excitement of the second odd dipole mode occurs which emits light into perpendicular sections of the X-waveguide. In the present letter we use this mechanism for optical diode. The device exploits only single micro cavity what is important with point of view of ultra compactness.

We assume, the linear L -shaped PhC waveguide is formed by removal of rows of dielectric rods as shown in Fig. 1. The waveguide supports band of guided TM mode spanning from the bottom band edge 0.315 to the upper one 0.41 in terms of $2\pi c/a$ with the electric field directed along the rods. This guided mode is even function along the line cross to waveguide. The microcavity is formed by three linear rods and one nonlinear rod. An asymmetric design of the microcavity provides the asymmetric coupling with the left and right legs of the waveguide. The material parameters of the cavity listed in Figure caption are chosen in so way that the dipole eigen frequencies of the microcavity belong the propagation band of the waveguide while other eigen modes remain beyond. The corresponding dipole modes

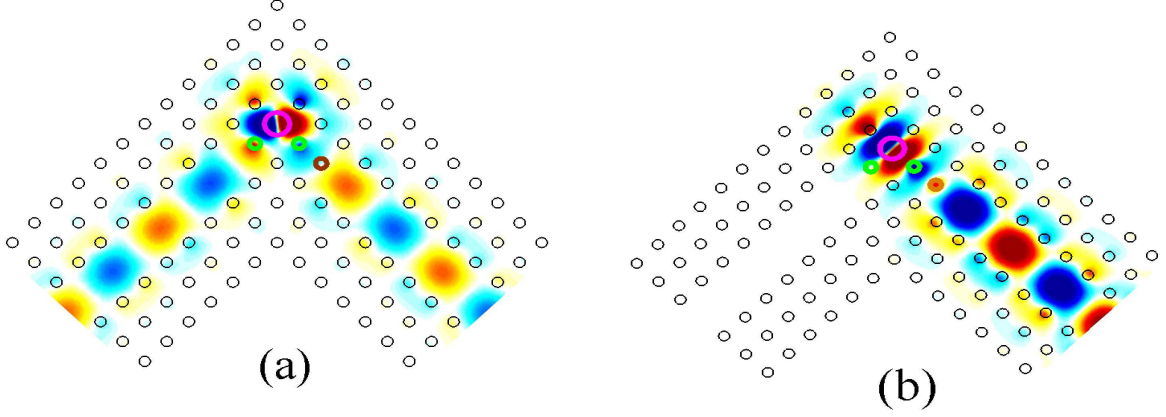


FIG. 1: (Color online) The nonlinear defect rod shown by open pink larger circle has the radius $0.4a$ and $\epsilon_0 = n_0^2 = 6.5$ and the nonlinear refractive index $n_2 = 2 \times 10^{-12} \text{cm}^2/\text{W}$ is placed into the corner of the L shaped waveguide formed by removal of dielectric rods in the two-dimensional square lattice PhC. The PhC lattice consisted of the GaAs dielectric rods with radius $0.18a$ and dielectric constant $\epsilon = 11.56$ where $a = 0.5 \mu\text{m}$ is the lattice unit. The additional two nearest rods (green in color) have radius $0.18a$ and $\epsilon = 11.56$. and third additional rod (brown in color) has radius $0.18a$ and $\epsilon = 5$ is substituted into the right leg of the waveguide in order to provide coupling asymmetry.

$E_1(\mathbf{x})$ and $E_2(\mathbf{x})$ obtained by numerical solution of the Maxwell equations have ordinary shape presented, for example, in Refs. [9, 10]. The dipole eigen frequencies in the design shown in Fig. 1 equal $\omega_1 a / 2\pi c = 0.3658$, $\omega_2 a / 2\pi c = 0.3650$. For linear limit when injecting light is small such a dipole microcavity will block a propagation of the TM mode of light in the L shaped waveguide ($T_L = T_R = 0$) because of orthogonality of the first/second dipole mode to the guided mode of right/left legs of the waveguide [7].

However in the case of the nonlinear dipole microcavity there might be a solution when both dipole modes can be excited simultaneously because of the nonlinear coupling between modes [9]. Therefore for definite frequency and intensity of injected light such a system can be opened for the light transmission. A window for the opening mostly depend on a ratio between the nonlinearity constant and the coupling strengths of the dipole modes of defect cavity with propagating modes of the waveguide [9]. Because of the coupling strengths of the dipole modes with propagating mode are different for the left and right legs of the L waveguide the thresholds for light transmissions from the left to the right and back will be different [3]. That is a key principle for the AOD in present PhC nonlinear structure.

The coupled mode equations [11] for the nonlinear dipole mode amplitudes have the following form [9]

$$\begin{aligned} i\dot{A}_1 &= [\omega_1 + V_{11} - i\gamma_1/2]A_1 + V_{12}A_2 + i\sqrt{\gamma_1}E_L e^{-i\omega t}, \\ i\dot{A}_2 &= [\omega_2 + V_{22} - i\gamma_2/2]A_2 + V_{21}A_1 + i\sqrt{\gamma_2}E_R e^{-i\omega t}, \end{aligned} \quad (1)$$

where E_L and E_R are the amplitudes of injecting light ingoing in the left and right legs respectively, A_1 and A_2 are the amplitudes of dipole modes, γ_1, γ_2 are the coupling strengths of the first and second dipole modes with propagating modes of the left/right legs of the L -shaped waveguide,

$$\langle m|V|n \rangle = -\frac{\omega_0}{2N_m} \int d^2\vec{r} \delta\epsilon(\vec{r}) E_m(\vec{r}) E_n(\vec{r}), \quad (2)$$

$$\delta\epsilon(\vec{r}) = \frac{n_0 c n_2 |E(\vec{r})|^2}{4\pi} \approx \frac{n_0 c n_2 |A_1 E_1(\vec{r}) + A_2 E_2(\vec{r})|^2}{4\pi}, \quad (3)$$

is the nonlinear contribution to the dielectric constant of the defect rod with instantaneous Kerr nonlinearity,

$$N_m = \int d^2\vec{r} \epsilon(\vec{r}) E_m^2(\vec{r}) = \frac{a^2}{c n_2} \quad (4)$$

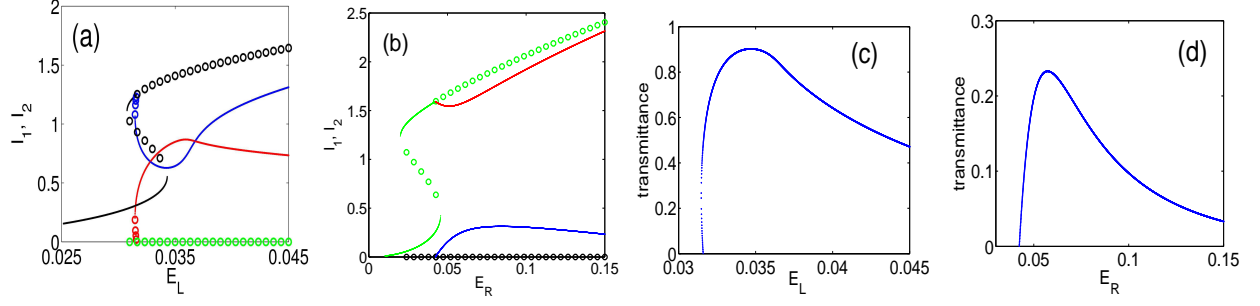


FIG. 2: (Color online) Intensities of dipole mode excitations vs light amplitude injected from the left E_L (a) and right E_R (b) for $\omega = 0.3618$. Open circles mark unstable solutions of Eq. (5). The ordinary solution inherited from the linear case which does not permit transmission is colored by black (I_1) and green (I_2). The bifurcated new solution intrinsic for nonlinear case opens transmissions colored by blue (I_1) and red (I_2). Transmittances corresponded to this bifurcated solution are shown in (c) and (d).

is the normalization constant of the eigen-modes with $\epsilon(\vec{r})$ as the dielectric constant of whole defectless PhC. After substitution of Eqs. (2) and (4) and $A_m(t) = A_m e^{-i\omega t}$ into the CMT equations (1) we write the stationary CMT equations in the dimensionless form

$$\begin{aligned} [\omega - \omega_1 + \lambda_{11}I_1 + \lambda_{12}I_2 + i\gamma_1/2]A_1 + 2\lambda_{12}Re(A_1^*A_2)A_2 &= i\sqrt{\gamma_1}E_L, \\ 2\lambda_{12}Re(A_1A_2^*)A_1 + [\omega - \omega_2 + \lambda_{22}I_2 + \lambda_{12}I_1 + i\gamma_2/2]A_2 &= i\sqrt{\gamma_2}E_R, \end{aligned} \quad (5)$$

where we introduced $I_m = |A_m|^2$ as the intensities of the dipole modes and dimensionless constants of nonlinearity

$$\lambda_{mn} = \frac{\omega_0 n_0 c^2 n_2^2}{8\pi a^2} \int_{\sigma} E_m^2(x, y) E_n^2(x, y) d^2 \vec{r} \quad (6)$$

where σ is the cross-section of the defect rod. Respectively, the outgoing transmission amplitudes to the left leg and to the right leg of the waveguide equal [11]

$$\begin{aligned} t_L &= \sqrt{\gamma_1}A_1 - E_L \\ t_R &= \sqrt{\gamma_2}A_2 - E_R. \end{aligned} \quad (7)$$

The results of numerical computation of the nonlinear CMT equations (5) altogether with Eqs. (7) are presented in Fig. 2 where we have taken for simplicity the dipole modes are degenerated: $\omega_1 = \omega_2 = 0.3655$. Substituting numerically calculated eigen dipole modes into Eqs.(6) we obtain $\lambda_{11} = \lambda_{22} = 0.002963$, $\lambda_{12} = 0.001035$. We calculated γ_1, γ_2 via widths of phase flips in reflection amplitude [12] for the linear dipole cavity. Fig. 2 (a) shows that for small amplitude injected from the left the second dipole mode is not excited. However when the amplitude E_L exceeds the threshold value E_{Lc} bifurcated solution arises with both dipole modes excited. As a result the transmission from the left to the right is opened while the transmission from the right to the left is still closed as shown in Fig. 2 (c, d). Similar threshold exists for transmission from the right to the left when $E_R > E_{Rc}$. However because of asymmetry of the design the threshold values for the right/left injected lights E_{Rc} and E_{Lc} are different. Thus, we obtained the AOD device with infinite transmission contrast between E_{Lc} and E_{Rc} . From Eqs. (5) we can find the threshold values by use of simple algebra from the condition that I_2 (Fig. 2 (a)) or I_1 (Fig. 2 (b)) tends to zero

$$\begin{aligned} \gamma_1 |E_{Lc}|^2 &= I_{1c}[(\omega - \omega_0 + \lambda_{11}I_{1c})^2 + \gamma_1^2/4] \\ \gamma_2 |E_{Rc}|^2 &= I_{2c}[(\omega - \omega_0 + \lambda_{11}I_{2c})^2 + \gamma_2^2/4], \end{aligned} \quad (8)$$

where

$$\begin{aligned} I_{1c} &= \frac{2(\omega_0 - \omega) \pm \sqrt{(\omega_0 - \omega)^2 - 3\gamma_2^2/4}}{3\lambda_{12}}, \\ I_{2c} &= \frac{2(\omega_0 - \omega) \pm \sqrt{(\omega_0 - \omega)^2 - 3\gamma_1^2/4}}{3\lambda_{12}}. \end{aligned} \quad (9)$$

Answer to the question which direction will be opened the first depends on sophisticated interplay between the resonance widths, on the frequency and the nonlinearity constants. Domains of AOD with infinite high transmission contrast which follow from Eqs. (8) and (9) are shown in Fig. 3 by red and green fields.

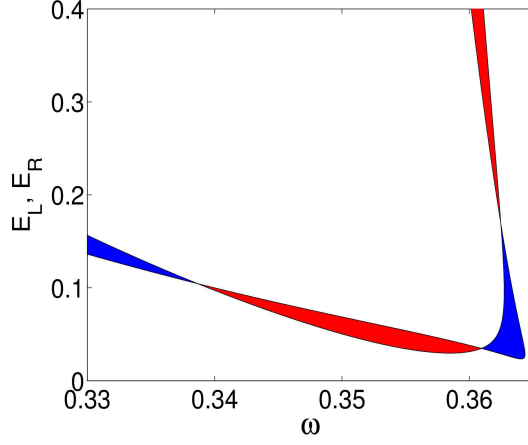


FIG. 3: (Color online) The domains of AOD. The domains of AOD from the left to the right is colored by blue while the domains of AOD from the right to the left is colored by red.

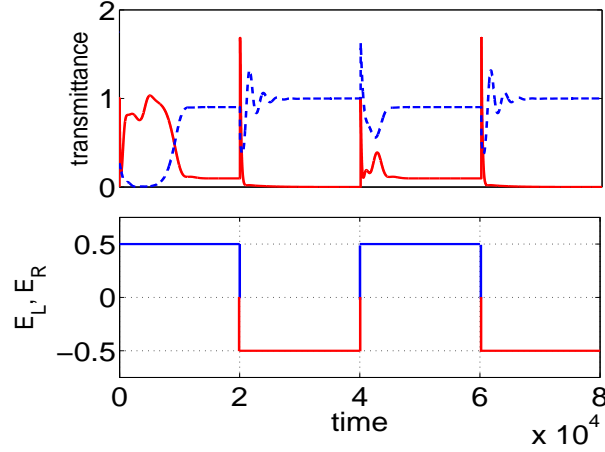


FIG. 4: (Color online) Time dependence of outputs to right leg (solid red line) and to left leg (dash blue line) which follow the alternating injected impulses. Below impulse launched from the left is marked by blue color and impulse launched from the right is marked by red color.

What is important the stable bifurcated solution belongs to the domain of AOD while the linear case inherited solution which blocks light transmission might be unstable in this domain as one can see from Fig. 2 (a, b), in particular for $\omega = 0.3618, E_L = 0.35, E_R = 0.35$. That can be used for opening and closing of light transmission, i.e., for optical switching. In Fig. 4 we show solution of temporal CMT equations (1). For the first impulse of light injected from the left with duration 2×10^4 (in terms $a/2\pi c$) we observe at first weak transmission to the right (shown by dash blue line) which is substituted by transmission close to 90%. The next impulse injected from the right blocks the output to the left for duration of impulse. The next series of impulses gives the same result. Thus, two impulses of light alternatingly injected from two legs of the L-shaped waveguide results in AOD effect with infinite transmission contrast.

In Fig. 5 we present transmittance of the system versus frequency for the bifurcated solution of the CMT equations (5) and compare the results with numerical calculation of the Maxwell equations for light transmission through the PhC design shown in Fig. 1. The numerical approach is described in detail in Ref. [9]. Patterns of stationary scattering wave function (real parts of electric field for the TM mode) are presented in Fig. 1 for the frequency $\omega = 0.3618$ and the injected power of light $P = 0.7W/a$. This point belongs to the blue domain in Fig. 3 where we have AOD from the left to the right. Respectively, Fig. 1 (a) shows that when light incidents from the left the bifurcated solution occurs with both dipole modes excited to permit the light transmission through the waveguide. Fig. 1 (b) shows that when light incidents from the right only single dipole mode is excited similar to the linear case. And therefore the light flow from the right to the left is blocked.

However numerics in PhC shown in Fig. 5 by open green circles does not reveal the domain of AOD from the right

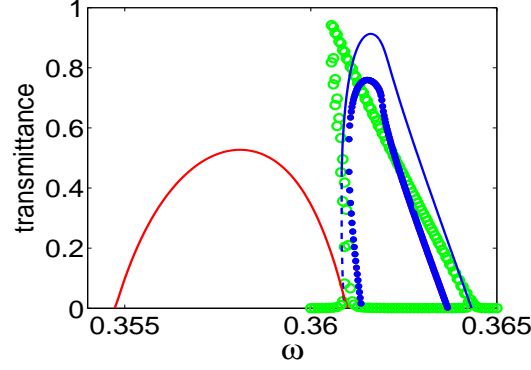


FIG. 5: (Color online) Transmittances vs frequency for $E_L = E_R = 0.035$. The CMT based transmittance with degenerated dipole modes is shown by solid lines where red line shows transmission from the right to the left, and blue line shows transmission from the left to the right. The case $\omega_1 a/2\pi c = 0.3658, \omega_2 a/2\pi c = 0.3650$ is presented by blue closed circles. Green open circles shows transmittance in PhC structure shown in Fig. 1 with $P = 0.7W/a$.

to the left in the frequency domain shown in Fig. 3 by red or by solid red line in Fig. 5 which follow from the CMT presented above. The reason is that the approximation of degeneracy of the dipole modes used in the CMT Eqs. (5). When the degeneracy was lifted the transmittance from the right to the left disappeared as shown in Fig. 5 by blue closed circles. Moreover that gives rise to fine splitting of the transmission peak.

This work was partially supported by RFBR grant 13-02-00497.

-
- [1] M. Scalora, J.R. Dowling, C.M. Bowden, and M.J. Bloemer, "The photonic band edge optical diode", J. Appl. Phys. J. Appl. Phys. **76**, 2023–2026 (1994).
 - [2] K. Gallo, G. Assanto, K.R. Parameswaran, and M.M. Fejer, "All-optical diode in a periodically poled lithium niobate waveguide", Appl. Phys. Lett. **79**, 314–316 (2001).
 - [3] W. Ding, B. Lukyanchuk, and C.-W. Qiu, "Ultra high-contrast-ratio silicon Fano diode", Phys. Rev. A **85**, 025806 (2012).
 - [4] S.F. Mingaleev and Yu.S. Kivshar, "Nonlinear transmission and light localization in photonic-crystal waveguides", J. Opt. Soc. Am. B **19**, 2241–2249 (2002).
 - [5] N.-S. Zhao, H. Zhou, Qi Guo, W. Hu, X.-B. Yang, S. Lan, and X.-S. Lin, "Design of highly efficient optical diodes based on the dynamics of nonlinear photonic crystal molecules", J. Opt. Soc. Am. B **23**, 2434–2440 (2006).
 - [6] X.-S. Lin, J.-H. Yan, L.-J. Wu, and S. Lan, "High transmission contrast for single resonator based all-optical diodes with pump-assisting", Opt. Express, **16**, 20949–20954 (2008).
 - [7] S. G. Johnson, C. Manolatu, S. Fan, P.R. Villeneuve, J. D. Joannopoulos, and H.A. Haus, "Elimination of cross talk in waveguide intersections", Opt. Lett. **23**, 1855–1857 (1998).
 - [8] M.F. Yanik, S. Fan, M. Soljačić, and J. D. Joannopoulos, "All-optical transistor action with bistable switching in a photonic crystal cross-waveguide geometry", Opt. Lett. **28**, 2506–2508 (2003).
 - [9] E.N. Bulgakov and A.F. Sadreev, "Symmetry breaking in photonic crystal waveguide coupled with the dipole modes of a nonlinear optical cavity", J. Opt. Soc. Am. B **29**, 2924–2928 (2012); "Giant optical vortex in photonic crystal waveguide with nonlinear optical cavity", Phys. Rev. B **85**, 165305 (2012); "All-optical manipulation of light in X- and T-shaped photonic crystal waveguides with a nonlinear dipole defect", Phys. Rev. B **86**, 075125 (2012).
 - [10] J. Joannopoulos, S.G. Johnson, J.N. Winn and R.D. Meade, *Photonic Crystals: molding the flow of light* (Princeton University Press, Princeton, N Y, 2008).
 - [11] W. Suh, Z. Wang, and S. Fan, "Temporal coupled-mode theory and the presence of non-orthogonal modes in lossless multimode cavities," IEEE J. of Quantum Electronics, **40**, 1511–1518 (2004)
 - [12] H.-W. Lee, "Generic Transmission Zeros and In-Phase Resonances in Time-Reversal Symmetric Single Channel Transport", Phys. Rev. Lett. **82**, 2358–2361 (1999).